Advancements in the Micromirror Array Projector Technology

D. Brett Beasley, Matt Bender, Jay Crosby, Tim Messer, and Daniel A. Saylor
Optical Sciences Corporation
www.opticalsciences.com
P.O. Box 8291
Huntsville, AL 35808

ABSTRACT

The Micromirror Array Projector System (MAPS) is a state-of-the-art dynamic scene projector developed by Optical Sciences Corporation (OSC) for Hardware-In-the-Loop (HWIL) simulation and sensor test applications. Since the introduction of the first MAPS in 2001, OSC has continued to improve the technology and develop systems for new projection and test applications. The MAPS is based upon the Texas Instruments Digital Micromirror Device (DMD)™ which has been modified to project high resolution, realistic imagery suitable for testing sensors and seekers operating in the UV, visible, NIR, and IR wavebands. This paper reviews the basic design and describes recent developments and new applications of the MAPS technology. Recent developments for the MAPS include increasing the format of the micromirror array to 1024x768 and increasing the binary frame rate to 10KHz. The MAPS technology has also been applied to the design of a Mobile Extended Spectrum Electro-Optical Test Set (MESEOTS). This test set is designed for testing UV, visible, NIR and IR sensors as well as laser rangefinders, laser trackers, and laser designators. The design and performance of the improved MAPS and the MESEOTS are discussed in paper.

Keywords: Infrared, Scene Projection, Digital Micromirror Device, Simulation, FPA testing, Hardware-in-the-loop.

1.0 INTRODUCTION

The Micromirror Array Projector System (MAPS) is a state-of-the-art dynamic scene projector developed by Optical Sciences Corporation (OSC) for Hardware-In-the-Loop (HWIL) simulation and sensor test applications. Since the introduction of the first MAPS in 2001, OSC has continued to improve the technology and develop systems for new projection and test applications. The MAPS is based upon the Texas Instruments Digital Micromirror Device (DMD)™ which has been modified by OSC for sensor test applications. This projector technology is capable of producing very realistic dynamic scenes in the UV, visible, NIR, and IR wavebands. The projector technology offers several attractive features including high spatial resolution, high frame rates, no dead pixels, and excellent uniformity. OSC now offers a family of commercial projector products including projectors, test-sets, and projector engines. In addition, the projector may be customized in a variety of configurations which are tailored to specific applications.

2.0 DMD BACKGROUND

The DMD is a micro-electromechanical system (MEMS) which has a 2-D array of individually controlled aluminum micro-mirrors. The DMD is the spatial light modulator in TI's Digital Light Processing™ (DLP™) system. DLP engines are manufactured by TI and sold to OEMs for use in display products such as business projection systems. DMDs are currently commercially available in a variety of formats with resolutions up to 1280x1024. Figure 1 shows a 1024x768 DMD package, and Figure 2 is an SEM image of the micromirrors with a grain of salt on the surface of the device.


Figure 1 – DMD Package

As depicted in Figure 3, each micromirror in the DMD can reflect light in one of two directions (±20° optical) depending upon the state of the underlying SRAM memory cell. With proper illumination, each mirror will reflect light into the pupil of the optical system when a “1” is written to its SRAM and out of the optical system when a “0” is written to its SRAM. The device is therefore binary in nature. The switching speed on the individual mirrors is approximately 10 usec. The binary image on the array can be updated at rates in excess of 10,000 Hz, and a global reset allows the entire image to be cleared in less than 20 usec. Intensity control is typically achieved using binary Pulse Width Modulation (PWM).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **Advancements in the Micromirror Array Projector Technology**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Optical Sciences Corporation,PO Box 8291,Huntsville,AL,35808**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**12**	

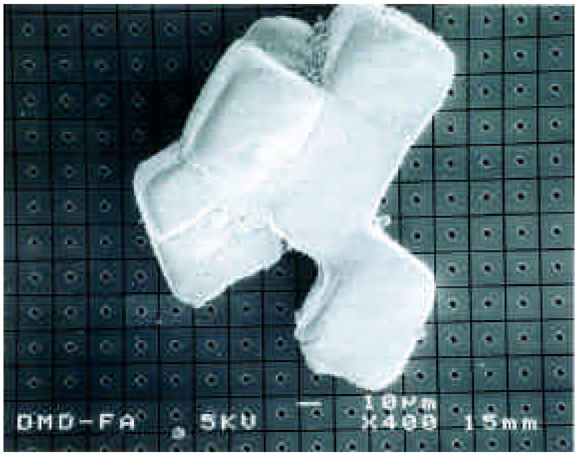

Figure 2: DMD with Grain of Salt on Surface

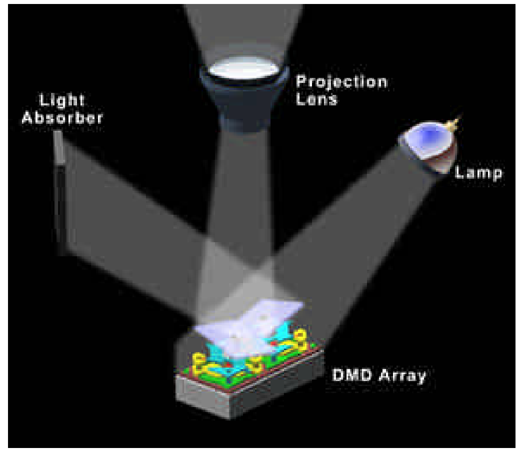

Figure 3: DMD Illumination

3.0 MAPS DESIGN OVERVIEW

3.1 System Block Diagram

Figure 4 shows the system level block diagram and interconnections for the MAPS. As shown in the figure, the complete projector system consists of three major components – the projector head, the support electronics, and the control PC. The projector head contains the DMD, DMD drive electronics, illumination source(s), illumination source controller, and collimator lens. The support electronics chassis contains the video converter electronics, sync signal processor, and power supplies. The control PC is not required for standard operations, but can be used to set the illumination source temperature and to input other operational parameters to the projector system.

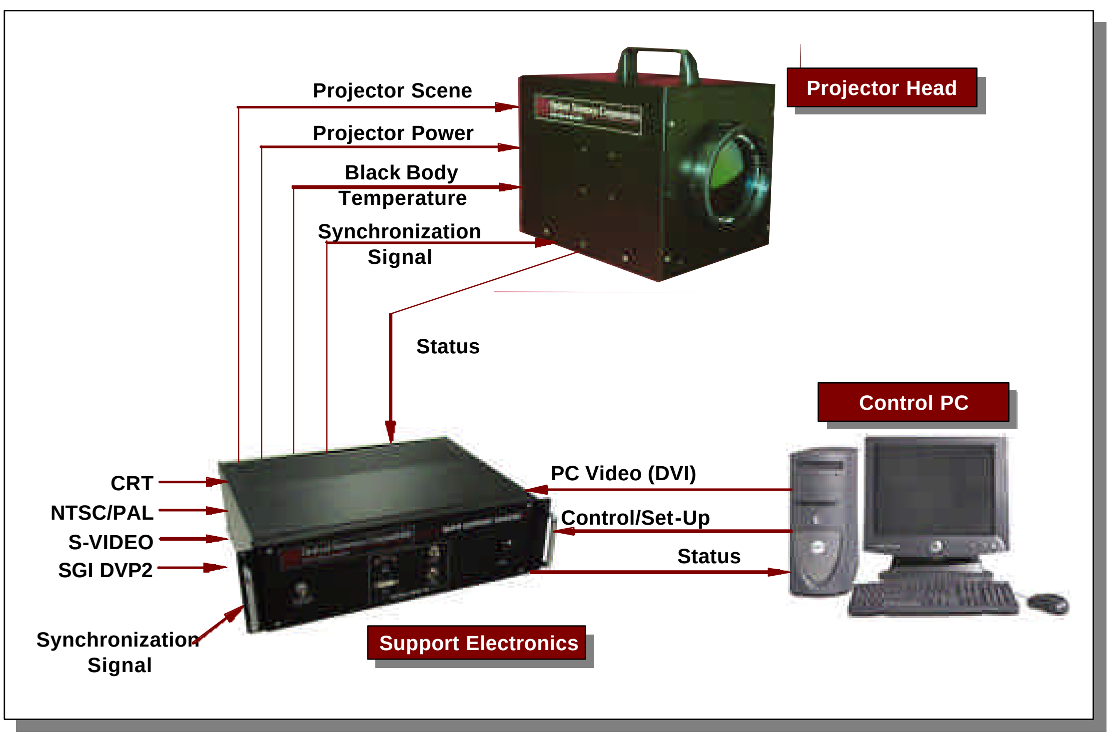

Figure 4: MAPS Block Diagram

3.2 MAPS Projector Head

The projector head contains the DMD, DMD drive electronics, illumination source(s), illumination source controller, and collimator lens. The design of several of these subsystems is discussed in the following sections.

3.2.1 Modified DMD

The window material used in the commercially available DMDs will not transmit wavelengths significantly outside the visible band. Therefore, one of the major design issues that had to be addressed in the development of the MAPS technology was the replacement of the DMD window. OSC has developed a technique for removing the visible window and installing a window which will transmit in the customer's waveband of choice while maintaining 100% mirror operability. Figure 5 shows the array formats offered, or soon to be offered, by OSC. The smallest array is an SVGA (800x600) format, the mid-sized array is an XGA (1024x768) format, and the largest array is an SXGA (1280x1024) format. OSC has successfully replaced the windows on numerous SVGA and XGA format DMDs with a variety of window materials and anti-reflection coatings, while maintaining 100% operability of the mirrors. OSC is currently developing the drive electronics for the SXGA format and plans to deliver the first SXGA system to a government customer in mid-2003.

Figure 5 – SVGA, XGA, and SXGA DMD Packages

3.2.2 DMD Drive Electronics

The DMD drive electronics are located in the projector head assembly at the rear of the DMD. Figure 6 is a photograph of one of the DMD drive electronics boards with the DMD mounted on the board. The functions of the drive electronics include:

- Receive the digital video from the support electronics
- Reformat the video for loading into the DMD and store in dual-port RAM
- Load video bit planes into the DMD in sync with the input sync signal
- Generate all required analog signals for the DMD
- Transmit status and receive control commands via the serial interface

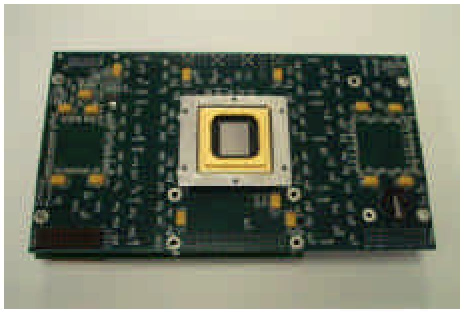

Figure 6 – Drive Electronics Board

In its most basic mode, the DMD can be operated in a single-bit "flickerless" manner. In this mode, binary images can be generated at high frame rates and there is no minimum integration time required for the UUT. In binary mode the MAPS is projecting the scene for ~97% of the frame time. During the remaining 3% of the frame time the mirrors are allowed to go to a "rest" state to prevent hinge memory. The timing of this rest event can be synchronized to the UUT so that it occurs during a time when the sensor is not integrating or during the "flyback" time of a scanning sensor. The rest time can actually be eliminated if necessary, however the lifetime of the device may be reduced. Give the reported MTBF lifetimes of greater than 100,000 hours for these devices, this would probably not be a problem for most applications.

Because the DMD is a binary device, gray scale intensities must be generated by Pulse Width Modulation (PWM) or some other technique such as half-toning. The PWM technique controls the intensity of each pixel by setting the percentage of time each mirror is in the "on" position within a given duration of time. Commercial (DLP) projectors utilize sequential PWM to generate 8-bit intensity values for three colors. The standard electronics in the DLP projector systems are designed to generate three 8-bit colors at a 60-85 Hz frame rate using PWM. Thus, it takes approximately 5.5 msec to generate an 8-bit image.

For sensor test applications, temporal aliasing will occur if the PWM is not synchronized properly with the sensor integration. OSC has developed the technique of synchronized PWM to address this issue. The synchronized PWM technique was implemented in MAPS by designing custom DMD drive electronics to drive the DMD in synchronization with the FPA integration (input sync signal). Figure 7 shows the basic technique of PWM where the entire PWM sequence occurs during

the sensor integration time. The DMD supports "latching" of the image such that the new image can be written to memory while the previous image is displayed. The Least Significant Bit (LSB) display time is typically ~15 usec and it takes ~100 usec to write a binary image into the DMD SRAM for the XGA device. Thus, for the LSBs there is some "dead time" where the scene is not displayed while waiting for the next binary image to be loaded into memory. This dead time can be effectively eliminated when displaying 6-bits or more, but increases the PWM sequence time when less than 6-bits are displayed.

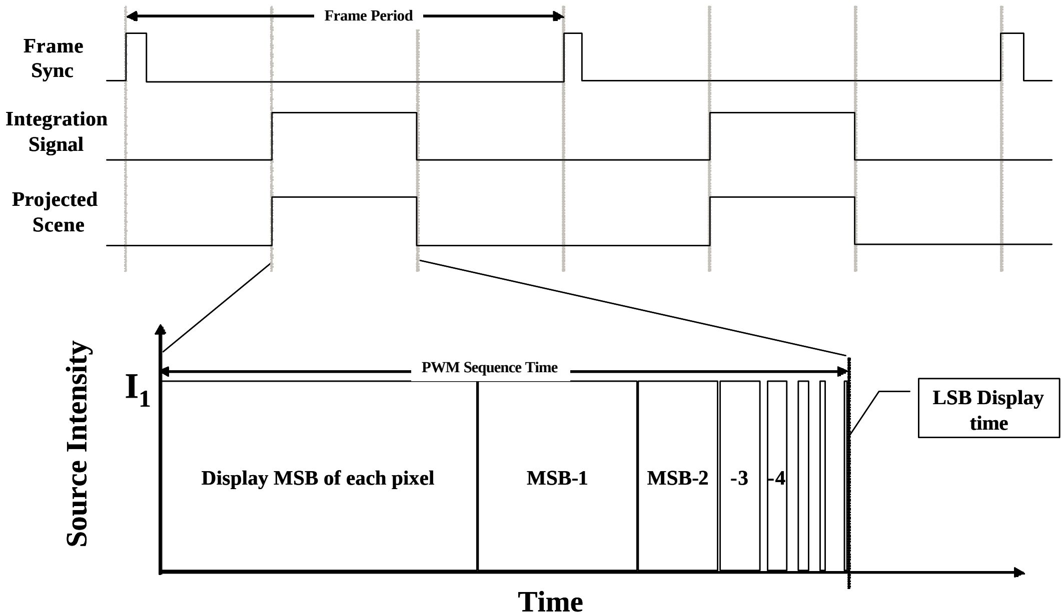

Figure 7: Synchronized PWM Timing

The length of the sensor integration time determines the maximum number of bits of resolution which can be generated. Longer sensor integration times allow more intensity levels to be achieved. Figure 8 shows the minimum integration time required to generate N bits of resolution. As an example, a typical integration time for an InSb FPA camera is 3 msec. With this integration time, the DMD can generate 128 (7-bits) intensity levels. The MAPS electronics are capable of monitoring the input sync signal and adjusting the PWM sequence timing automatically to match the integration time and maximize the bit resolution with only one sync period of lag. Because of the DMD's binary nature and the stability of the master clock, the intensity levels are very accurate and linear.

800x600 DMD Display Timing

Minimum UUT Integration Time			
Image Mode		*One Shot Mode (ms)*	*Effective DMD Frame Rate*
1bit		0.246	4065.041
2bit		0.294	3401.361
3bit		0.603	1658.375
4bit		0.975	1025.641
5bit		1.223	817.661
6bit		1.719	581.734
7bit		2.711	368.868
8bit		4.695	212.993
9bit		8.663	115.433
10bit		16.599	60.245
11bit		32.471	30.797
12bit		64.215	15.573
13bit		126.000	7.937
14bit		248.500	4.024

Figure 8 – Integration Time vs. #Bits

3.2.3 Illumination Source

The DMD is illuminated by a source which emits radiation in the waveband of interest. Because the DMD is capable of generating scenes in any waveband from the UV to LWIR the illumination source may be one of several types of sources. For IR applications, extended area blackbody sources are typically used to illuminate the DMD. In addition to the single illumination source configuration, OSC has developed a dual-blackbody configuration for IR applications. In the dual-blackbody configuration a "cold blackbody" is used to illuminate the off-side of the DMD, which improves the contrast and reduces the minimum apparent temperature. In addition to improving the minimum apparent temperature, the dual-blackbody configuration also allows differential control of the blackbodies which is useful for precision testing of IR sensors. For visible and NIR applications a halogen bulb source is typically used.

3.3 Support Electronics

The MAPS support electronics are housed in a standard 3U 19" rack mount chassis. The functions of the support electronics include:

- Receive the video from either a DVP2, DVI, RS-170/PAL, RGB-HV (CRT), or S-video source
- Convert/digitize the video and send to the DMD drive electronics
- Receive the input sync signal and modify as commanded by the user via software
- House the power supplies for the electronics and illumination sources
- Transmit status and receive control commands via the serial interface

Figure 9 is a photograph of the standard support electronics chassis.

Figure 9: MAPS Support Electronics Chassis

3.4 Control PC

The control PC allows the user to modify the projector operational parameters and monitor the status of the projector. The PC communicates with the support electronics via an RS232 serial port.

3.4.1 Control Software

The MAPS includes control software which will run on any Microsoft Windows-based PC. This software allows the user to control and monitor the projector operational parameters via the computer's serial interface. Figure 10 shows one of the windows from the control software. The top-half of this window allows the user to set the dual-blackbody source temperatures and load a calibration file which will set the blackbody temperature required to generate the desired apparent temperature. The bottom half of the window displays the status of the blackbody sources and the other parameters of the projector system.

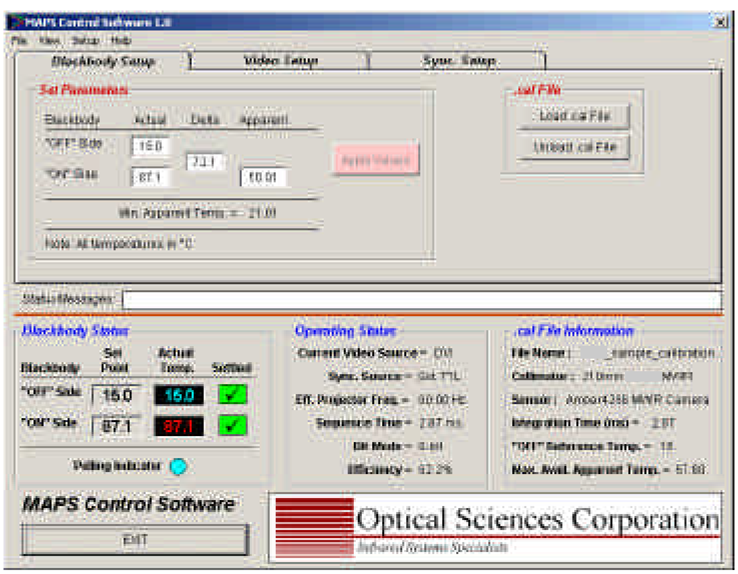

Figure 10 – MAPS Control Software

4.0 RECENT DEVELOPMENTS AND CURRENT STATUS

The following sections discuss recent developments in the MAPS technology, examples of systems manufactured to-date, and the current status of the various array formats.

4.1 SVGA (800x600) MAPS

The SVGA format MAPS projector was commercially introduced in April 2001. It is now in full-production and available in various wavebands and configurations. Figure 11 shows a typical infrared band MAPS system. This particular system included two interchangeable collimators – one for projecting a narrow FOV image and the other for projecting a wide FOV image. The IR MAPS is available in single or dual-blackbody configurations. The dual-blackbody configuration allows the user to control the illumination blackbodies in both absolute and differential temperature mode.

Figure 11 – IR-MAPS Projector With Dual Collimators

A custom visible-band MAPS was designed and fabricated for a government HWIL facility customer. The MAPS-Visible system projects a dynamic visible image that can be directed onto a visible detector array. This projector was designed for testing low light level visible band sensors of various formats and detector pitches without objective optics. The optical system was therefore designed as a continuously variable zoom relay lens which relays the image of the DMD onto the sensor FPA under test. The image size can be varied from approximately 4.9mm x 3.7mm to 34.5mm x 25.9mm, which equates to a total zoom range of approximately 0.36X to 2.54X. The large zoom range allows the image size to be matched to many different sensor array sizes. Figure 12 is a photograph of the visible projector system and Figure 13 is a sample image collected by a 1024x1024 CCD array.

Figure 12: MAPS-Visible Projector

Figure 13: MAPS-Visible Sample Image

In addition to the complete projector systems, OSC has developed a MAPS engine product for customers who want to design/utilize their own illumination source and optics. The MAPS engine includes the DMD (with customer selected window), the DMD drive electronics and the support electronics. The DMD and drive electronics are housed in an enclosure, but full access to the front of the DMD is provided. Figure 14 shows the front and back side of the MAPS projector engine chassis. The DMD can be seen on the front side of the chassis while the power and video connections as well as image flip switches are located on the back side of the chassis.

Figure 14: MAPS Projector Engine

4.2 XGA (1024x768) MAPS

OSC has completed development of the XGA format (1024x768) MAPS. This DMD has more than 786,000 individually controllable micromirrors which is a 33.33% increase in the number of mirrors from the SVGA version. In addition to the increased resolution, this projector format also offers an improved binary frame rate. OSC has demonstrated a binary frame rate in excess of 10KHz for this DMD compared to 4065 Hz for the SVGA format. Another useful feature of the XGA format DMD is the capability for phased reset. This feature allows groups of mirrors to be reset individually instead of a global reset for the entire array. This allows for flexibility in the PWM time which can be used to reduce the minimum integration time required to display an N-bit PWM sequence. Utilizing phased reset while displaying 6-bits or more allows the PWM sequence time to be reduced to its theoretical minimum which is given by:

$$t_{PWM} = t_{LSB} \bullet 2^{(N-1)}$$

Where:

N = The number of bits of amplitude resolution

$\hat{o}_{PWM}$ = Time required to complete the PWM sequence

$\hat{o}_{LSB}$ = Display time for the least significant bit

4.3 1280x1024 Array Development

OSC is currently developing the SXGA format (1280x1024) MAPS. This DMD has more than 1.3 million individually controllable micromirrors, which is a 173% increase in the number of mirrors from the SVGA version. This projector format will operate at a binary frame rate of approximately 7.5KHz. We are anticipating that the SXGA MAPS systems will be available in late 2003.

5.0 MAPS PERFORMANCE

5.1 Performance Summary

Table 1 below summarizes the performance characteristics of the MAPS.

Parameter	Performance
Spectral Range	UV to LWIR available. Determined by illumination source and optics.
Format	800x600 (SVGA) 1024x768 (XGA) 1280x1024 (SXGA) (Available late 2003)
Pixel Pitch	17 um
Maximum Binary Frame Rate	4065 Hz. (SVGA) 10,000 Hz. (XGA) 7,500 Hz. (SXGA)
Address Mode	Snapshot
Max. Duty Factor	~97%
Amplitude Resolution	1-24 bit programmable.
Contrast Ratio	400:1 Visible ~250:1 MWIR 15:1 LWIR (Normal Mode) 110:1 (Special Mode)
Max Apparent Temperature	>800K (Dependent upon source selected)
Pixel Operability	100%
Spatial Uniformity	>99.8%
Size	~8.5"x9.0"x10.5" (Dependent upon optical system)
Interfaces	PC (CRT), DVI, NTSC, PAL, S-Video, DVP2
Power Consumption	~7W – DMD, 50W - System

Table 1: Micromirror Array Projector System Performance Summary

5.2 Apparent Temperatures and Contrast

The maximum and minimum apparent temperatures of the IR-MAPS are dependent upon the illumination source temperature. Figure 15 shows the maximum and minimum apparent temperature of a MAPS operating in the MWIR band as a function of illumination source temperature. This data is used to calculate the contrast ratios shown in the performance summary above.

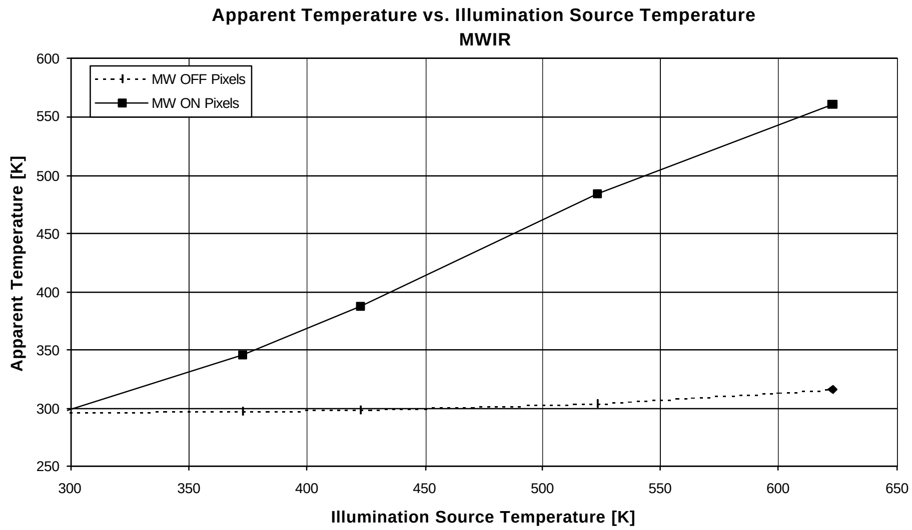

Figure 15: MWIR Apparent Temperature vs. Illumination Source Temperature

Figure 16 shows the maximum and minimum apparent temperature of a MAPS operating in the LWIR band as a function of illumination source temperature. Note that the data is shown for two modes of operation – normal mode (NM) and special mode (SM). The special mode of operation is a proprietary technique of operating the DMD which can be used to significantly enhance the contrast in the LWIR band under certain conditions.

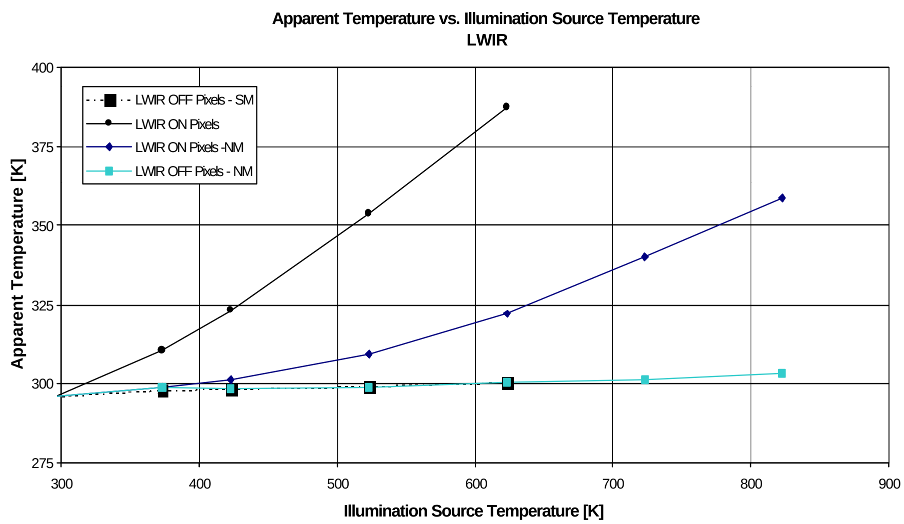

Figure 16: LWIR Apparent Temperature vs. Illumination Source Temperature

5.3 Sample Images

Three sample images collected from two MWIR MAPS and one LWIR MAPS are shown in Figures 17, 18, and 19. The image in Figure 17 was projected by a SVGA MWIR MAPS operating at 6 bits of amplitude resolution and collected by a 320x240 InSb FPA camera. The image in Figure 18 was projected by an XGA MWIR MAPS operating at 7 bits of amplitude resolution and collected by a 256x256 InSb FPA camera. The image in Figure 19 was projected by a SVGA LWIR MAPS operating at 8 bits of amplitude resolution and collected by a 320x240 uncooled bolometer array camera.

Figure 17: MWIR SVGA Collected by 320x256 InSb FPA camera

Figure 18: MWIR XGA Collected by 256x256 InSb FPA camera

Figure 19: LWIR SVGA Collected by 320x240 Uncooled Bolometer Array Camera

6.0 MOBILE EXTENDED SPECTRUM ELECTRO-OPTICAL TEST SET

The DMD utilizes aluminum micromirrors which have excellent reflectivity from the UV to the LWIR bands. It is therefore unique in its ability to generate dynamic scenes in virtually all of the wavebands of interest to customers testing electro-optic (EO) sensors. The DMD also offers the potential for specialized modulated source simulation and laser testing. Recognizing the unique capability of the MAPS technology to enhance EO test capabilities across a broad spectrum of wavelengths, the U.S. Army awarded OSC a Phase II Plus SBIR contract to develop a Mobile Extended Spectrum EO Test Set (MESEOTS). The MESEOTS is a prototype advanced EO test set which will be capable of projecting dynamic imagery as well as performing automated testing of a large variety of EO sensors and systems operating in the UV, visible, NIR, MWIR and LWIR spectral bands. The prototype mobile extended spectrum EO test set will be capable of performing an unprecedented variety of test functions including: FLIR testing, MWIR scene simulation, visible camera testing, direct view optics testing, visible scene simulation, UV sensor testing, UV scene simulation, laser rangefinder testing, laser power measurement, laser beam divergence measurement, laser receiver testing, laser spot tracker testing, modulated source simulation, and boresight testing.

6.1 MESEOTS Design

Figure 20 shows the functional block diagram of the MESEOTS. The heart of the system is a 1280x1024 DMD with a broadband window. The DMD is illuminated by a variety of sources including a UV source, a visible/NIR source, a 1.064 um laser source, a 1.55 um laser source, and dual differential blackbody sources. All of these sources allow the DMD to project dynamic scenes and static test patterns in most of the wavebands and wavelengths of interest to the EO tester. The laser sources also have a detector and delay electronics to support the testing of laser rangefinders. In addition, a laser energy meter combined with the DMD acting as a variable aperture allows the MESEOTS to measure laser divergence and energy levels. Another key feature of the MESEOTS is its ability to perform boresight testing of a sensor suite.

Figure 21 shows the block diagram of the MESEOTS system. It is comprised of the DMD, an all reflective collimator, a laser power meter, multiple illumination sources, and the associated drive electronics for each subsystem.

Figure 22 shows the CAD model of the final MESEOTS system. The MESEOTS is currently being fabricated and is scheduled for delivery to the Army in mid-2003.

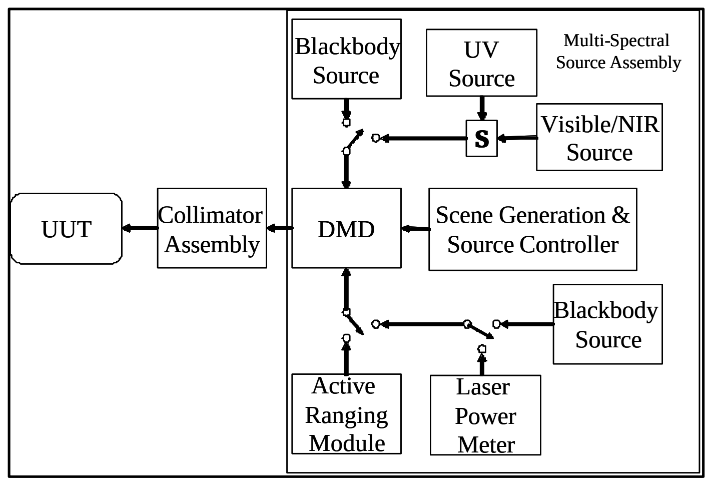

Figure 20: MESEOTS Functional Block Diagram

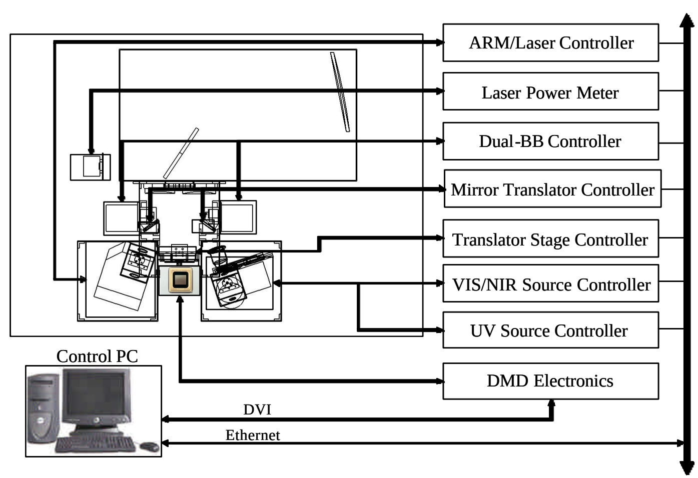

Figure 21: MESEOTS Block Diagram

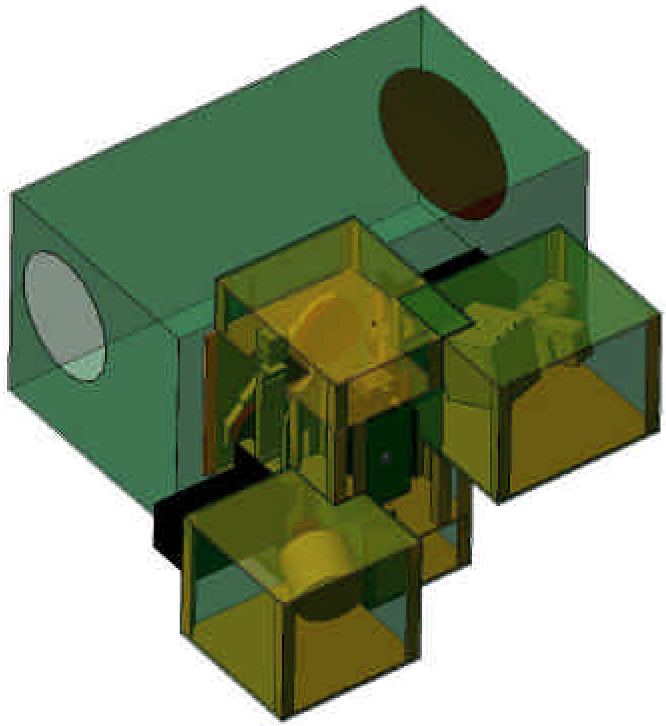

Figure 22: MESEOTS CAD Model

7.0 ACKNOWLEDGMENTS

Portions of this work were sponsored by the US Army Aviation and Missile Command's Research, Development, and Engineering Center under the Phase II and Phase II Plus Small Business Innovative Research Contract DAAH01-00-C-R093. The authors would like to thank Mr. Alex Jolly, Mr. Bill Sholes, Mr. Scottie Mobley, and Mr. Jim Buford, all of USAAMCOM, and Mr. Eddie Burroughs and Mr. Richard Brown of USA RTTC for their support of our efforts. The authors would also like to thank our colleagues at OSC, Dr. Mike Cornell, Mr. Charles Naumann, and Mr. Rob Cabra, for their support.

8.0 TRADEMARKS